Freeze-Out of Strange Hadrons at RHIC
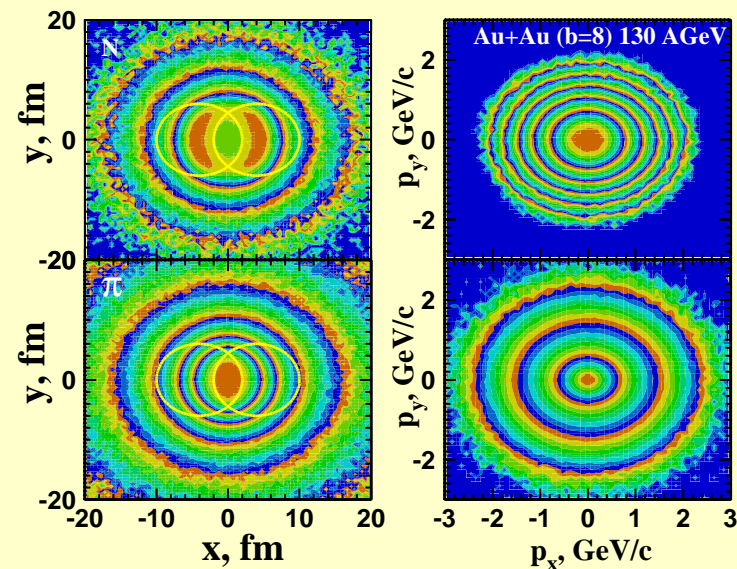
Larisa Bravina
Department of Physics, University of Oslo

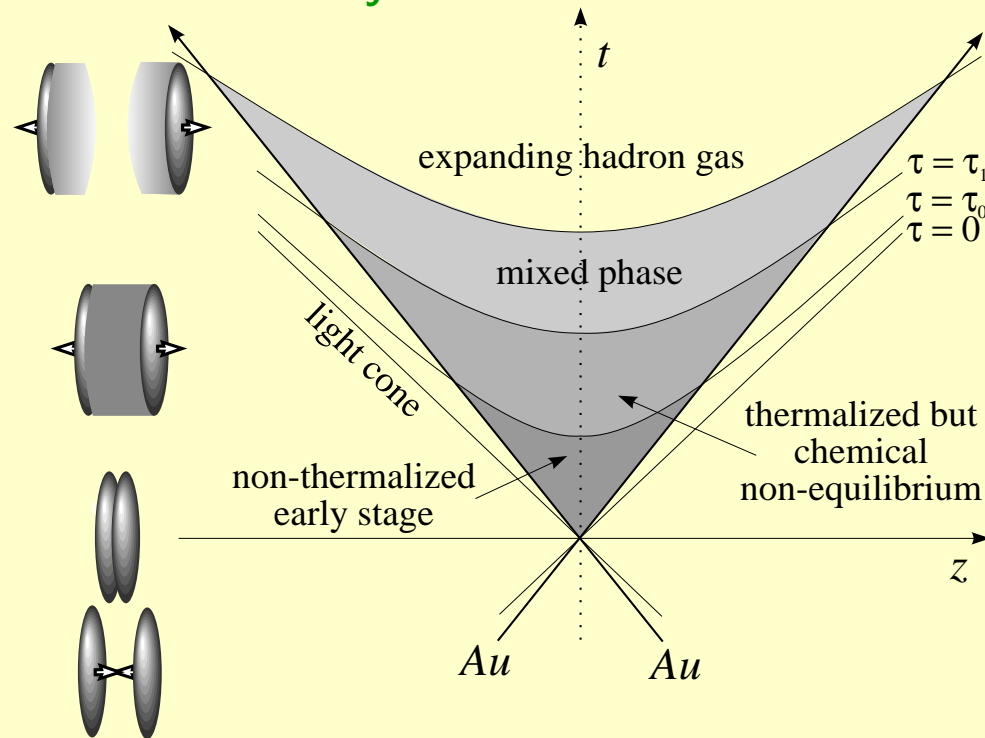**September 16, 2004**
SQM 2004

❖ **Motivation**

❖ **Model description**

❖ **Features of the freeze-out of particles in microscopic model**

❖ **Freeze-out at RHIC. Comparison with lower energies**

❖ **Freeze-out and the development of elliptic flow**

❖ **Conclusions**

Introduction

Relativistic Heavy Ion Collisions - Tool to Probe Hot and Dense Nuclear Matter

We study separately the last interaction points of hadrons produced in inelastic and in elastic collisions, as well as in resonance decays

❖ **inelastic collisions $\rightarrow$ chemical equilibration**

❖ **elastic collisions $\rightarrow$ thermal equilibration**

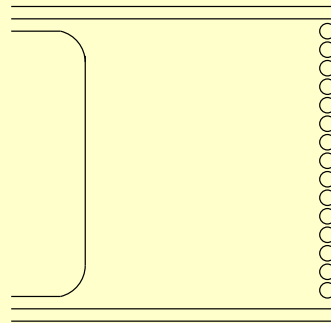❖ **resonance decays $\rightarrow$ characterize mostly the individual properties of the emitted particles.**

We investigate $d^2N/dzdt$, $d^2N/r_T dr_T dt$, $d^2N/dy_{cm} dt$, $d^2N/m_T dm_T dt$ and their projections on the t-, z-, r_T-, y- and m_T-axes
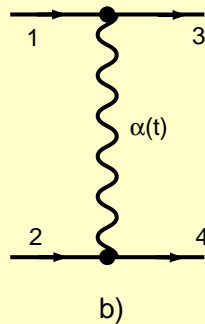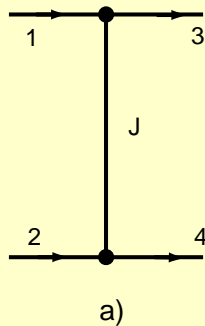
Dual Topological Unitarization Models

These models are based on Gribov-Regge field theory (color exchange)

Planar digram

In hh interactions a one-string mechanism (with quark-antiquark annihilation) is possible in $p\bar{p}$ collisions but not in pp
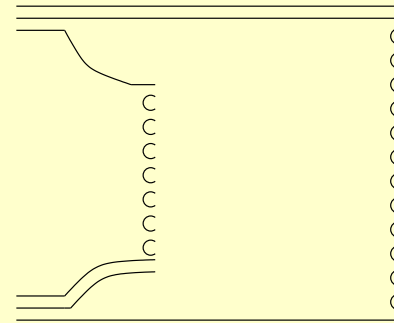
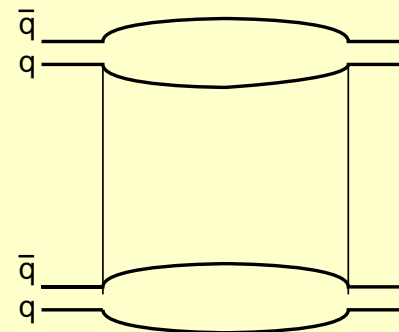## Cylinder digram

The simplest topology which contribution does not vanish at $s \to \infty$ is a two-string diagram

Such a diagram corresponds to the **Reggeon exchange** in the GRT (weight $\propto 1/N$; contribution $\propto s^{-1/2}$)

Such a diagram corresponds to the **Pomeron exchange** in the GRT (weight $\propto 1/N^2$). Its square has the topology of a cylinder

Hard processes and multi-Pomeron exchanges

The inelastic hh cross section $\sigma_{\mathbf{in}}(\mathbf{s})$ can be calculated via the real part of the eikonal $\mathbf{u}(\mathbf{s}, \mathbf{b})$

$$\sigma_{\mathbf{in}}(\mathbf{s}) = 2\pi \int\limits_{0}^{\infty} \left\{ 1 - \exp\left[-2\mathbf{u}^{\mathbf{R}}(\mathbf{s}, \mathbf{b}) \right] \right\} \mathbf{b}\,d\mathbf{b}$$

The eikonal can be presented as a sum of three terms corresponding to soft and hard Pomeron exchange, and triple Pomeron exchange, which is responsible for the single diffraction process,

$$\mathbf{u}^{\mathbf{R}}(\mathbf{s}, \mathbf{b}) = \mathbf{u}^{\mathbf{R}}_{\mathbf{soft}}(\mathbf{s}, \mathbf{b}) + \mathbf{u}^{\mathbf{R}}_{\mathbf{hard}}(\mathbf{s}, \mathbf{b}) + \mathbf{u}^{\mathbf{R}}_{\mathbf{triple}}(\mathbf{s}, \mathbf{b})$$

Using the Abramovskii-Gribov-Kancheli (AGK) cutting rules we get

$$\sigma_{\mathbf{in}}(\mathbf{s}) = \sum_{\mathbf{i,j,k=0};\mathbf{i+j+k\geq 1}} \sigma_{\mathbf{ijk}}(\mathbf{s}) \ ,$$

$$\sigma_{\mathbf{ijk}}(\mathbf{s}) = 2\pi \int\limits_{0}^{\infty} \mathbf{b}\,d\mathbf{b} \exp\left[-2\mathbf{u}^{\mathbf{R}}(\mathbf{s}, \mathbf{b}) \right]$$

$$\times \ \frac{\left[2\mathbf{u}^{\mathbf{R}}_{\mathbf{soft}}(\mathbf{s}, \mathbf{b}) \right]^{\mathbf{i}}}{\mathbf{i!}} \frac{\left[2\mathbf{u}^{\mathbf{R}}_{\mathbf{hard}}(\mathbf{s}, \mathbf{b}) \right]^{\mathbf{j}}}{\mathbf{j!}} \frac{\left[2\mathbf{u}^{\mathbf{R}}_{\mathbf{triple}}(\mathbf{s}, \mathbf{b}) \right]^{\mathbf{k}}}{\mathbf{k!}} \ .$$

The last equation enables one to determine the number of strings and hard jets.

Freeze-Out at SPS

$\mathrm{d^2N/dzdt}$ distribution of the final state hadrons over (t, z)- coordinates of their last elastic and inelastic collision points

$\mathrm{d^2N/d\eta\tau d\tau}$-distribution of pions over the variables $(\eta, \ \tau)$

(a)

Freeze-out of pions in S+S and Pb+Pb at 160 AGeV
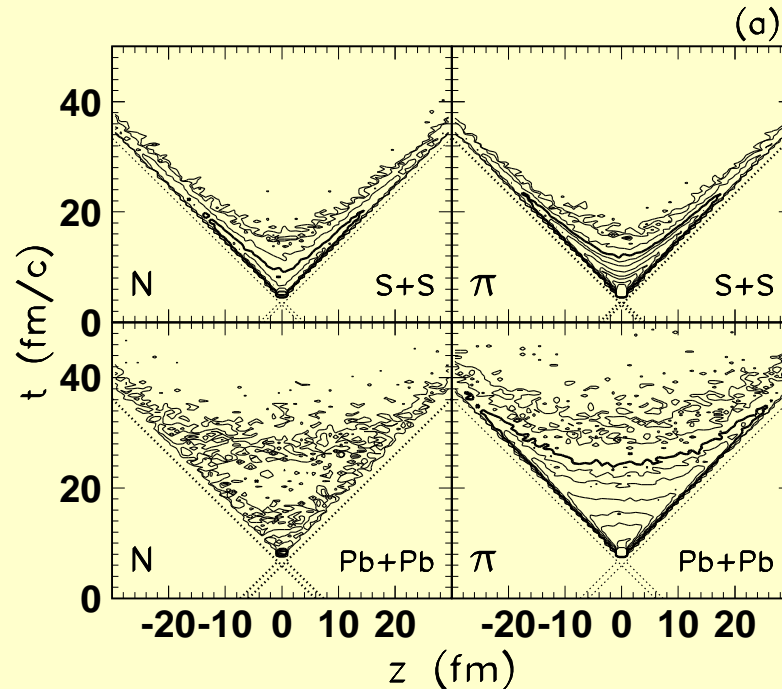
Although the shape of the contours is similar to the Bjorken proper-time surface, the particles in QGSM are emitted from the whole available space-time region
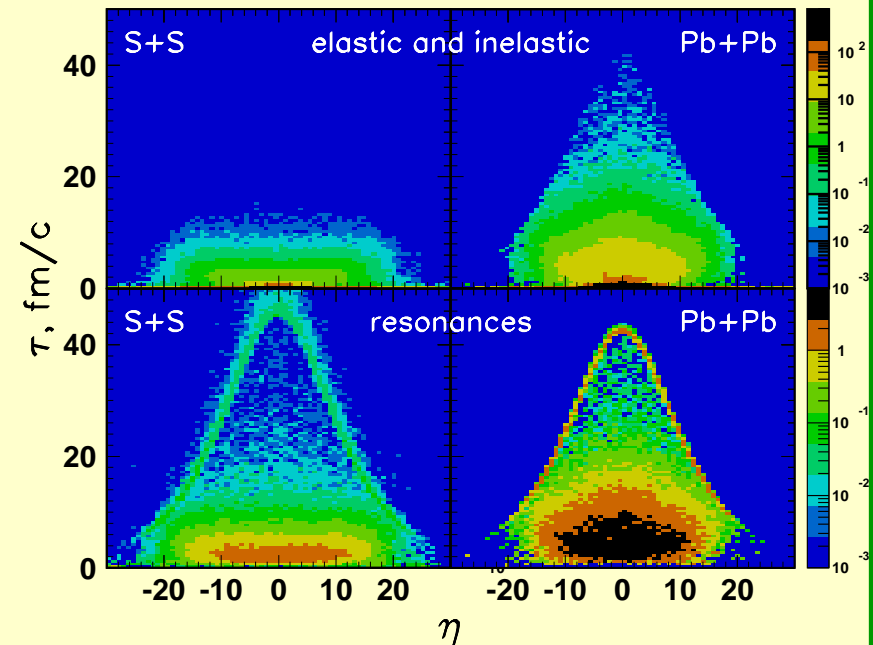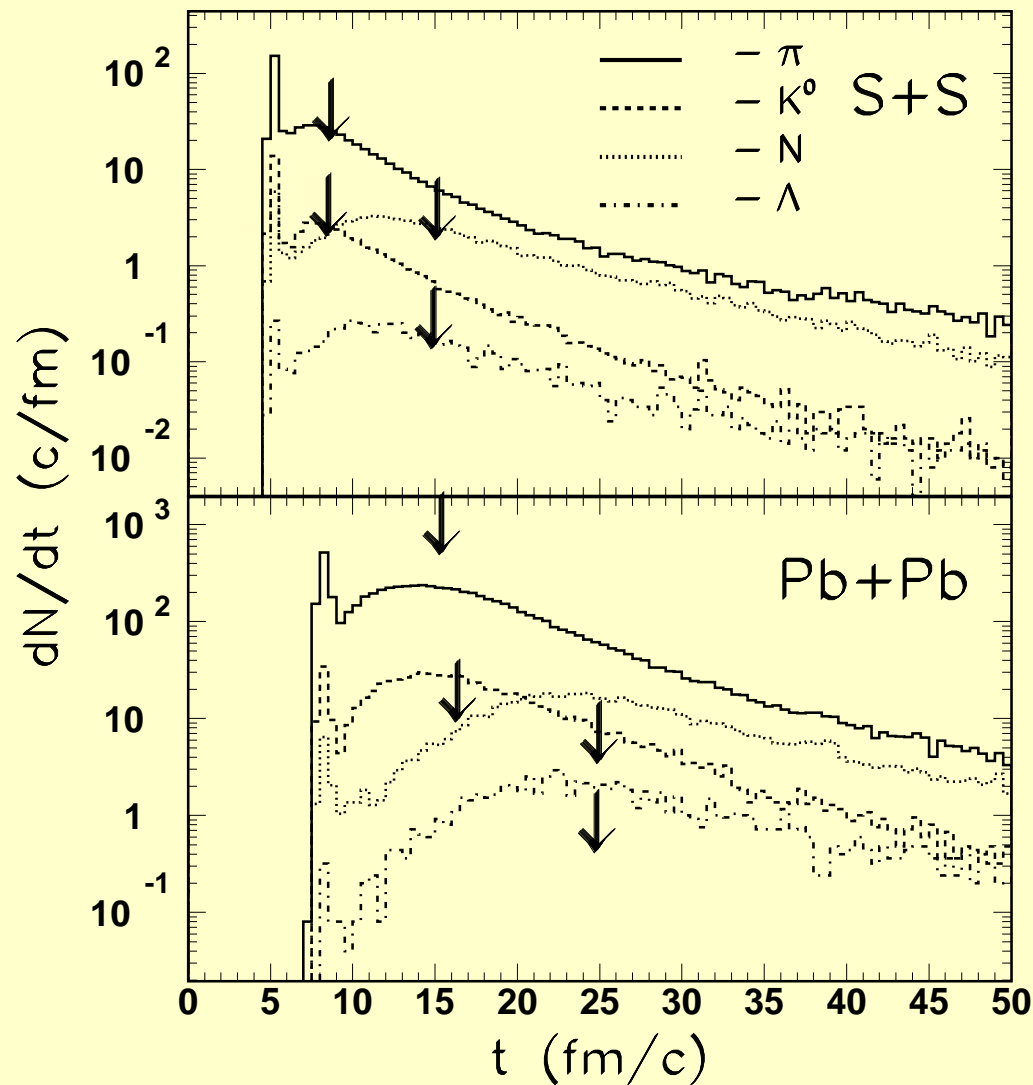
In these variables the sharp Bjorken freeze-out would look like hypersurface $\tau = \mathrm{const}$. The resonances produce the long tail in the (τ, η)-plot which is strongest pronounced in the case of the S+S collision

Sequential Freeze-Out

dN/dt-distribution of the particles over their last collision time, **t**. The vertical arrows correspond to the average emission times of the species.
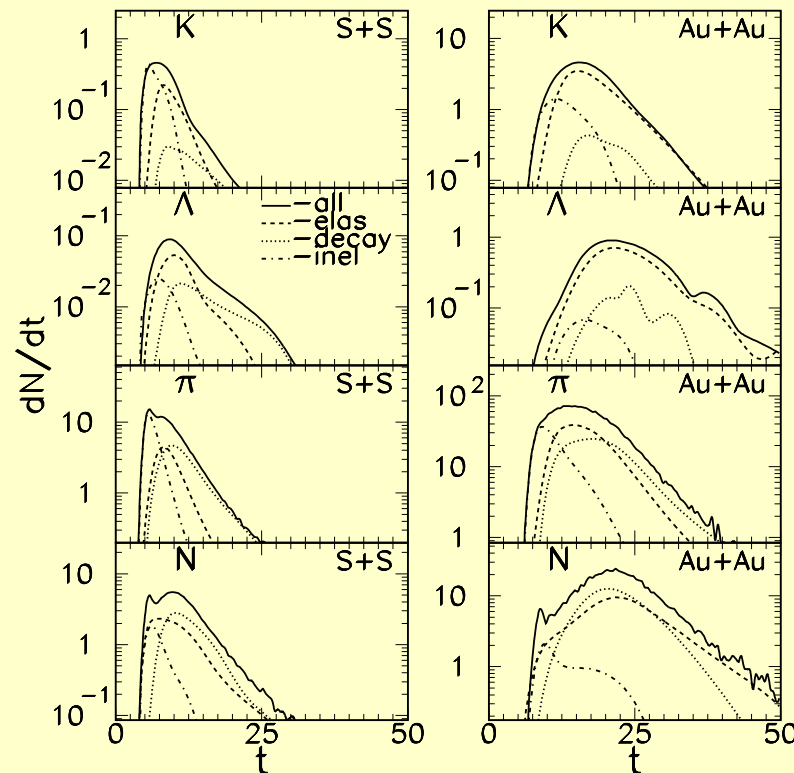
There is no unique freeze-out time for different hadrons. Mesons are emitted by about **10(6) fm**/c earlier than baryons in **Pb+Pb (S+S)** collisions at **160 AGeV/c**. This conclusion is valid also for the particles emitted in a certain rapidity interval, e.g. $|\mathbf{y}| \leq \mathbf{1}$.

Sequential Freeze-Out

AGS

RHIC

Au+Au at 130 AGeV
N in QGSM
π
Λ
K
Φ

dN/dt^{freeze} (a.u.)

t^{freeze} (fm/c)

dN/dt

t

t

Freeze-out order: 1 - pions; 2 - kaons; 3 - lambdas; 4 - nucleons
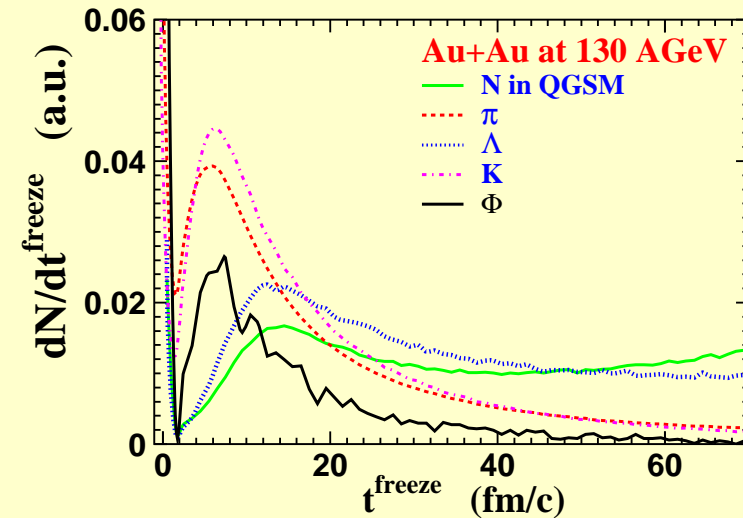
**(1)** compared to lower energies, many hadrons leave the system immediately after their production

(2) mesonic distributions are peaked at $t = 8 - 10\,\mathbf{fm}/c$

(3) distributions of baryons are wider due to the large number of rescatterings

Freeze-Out at RHIC

$d^2N/p_t dp_t dt$ and $d^2N/r_t dr_t dt$ distribution of the final-state hadrons over their last (elastic or inelastic) collision point.
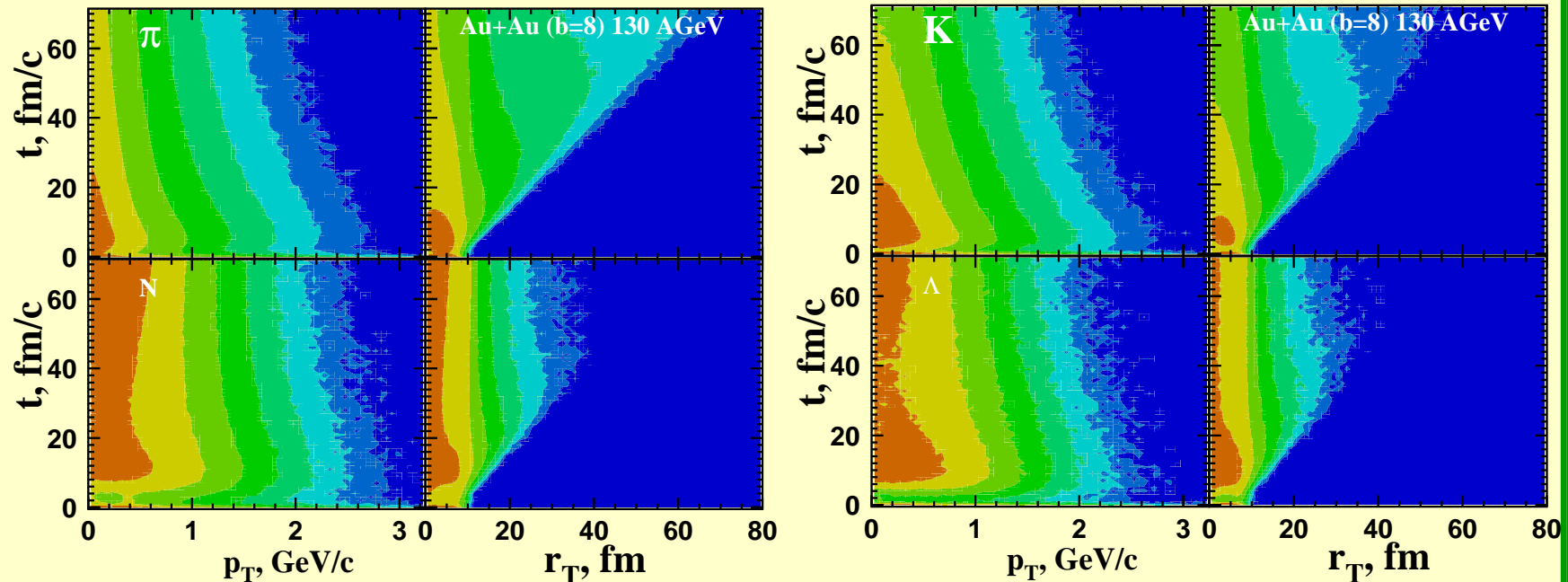
(1) Compared to SPS, not only pions but also many kaons, nucleons and lambdas are emitted from the surface region $r_T \approx R_A$ within first fm/c.
(2) A strong collective transverse expansion of hadronic matter is observed.

Freeze-Out and Elliptic Flow

Au+Au (b=8 fm) at $\sqrt{s} = 130$ **AGeV**

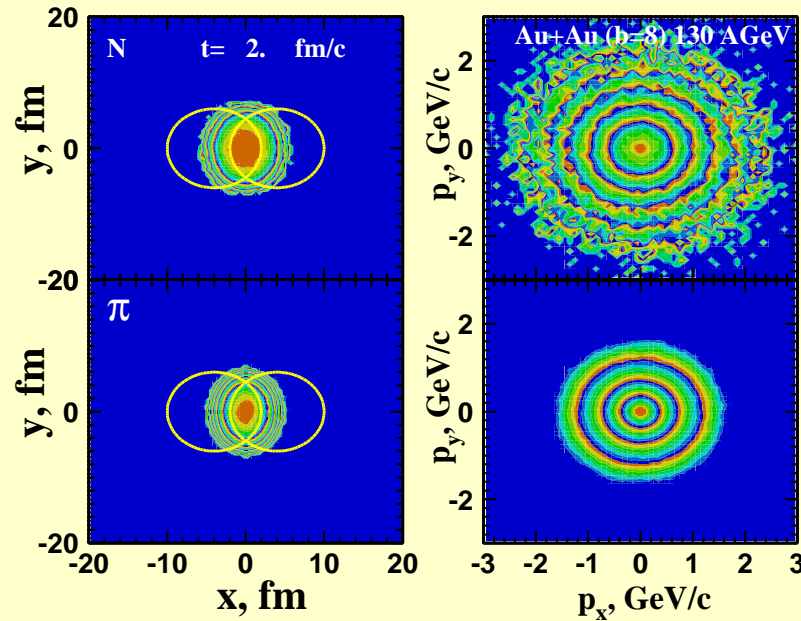$dn/dt_{\text{freeze-out}}$

$v_2(y=0)$
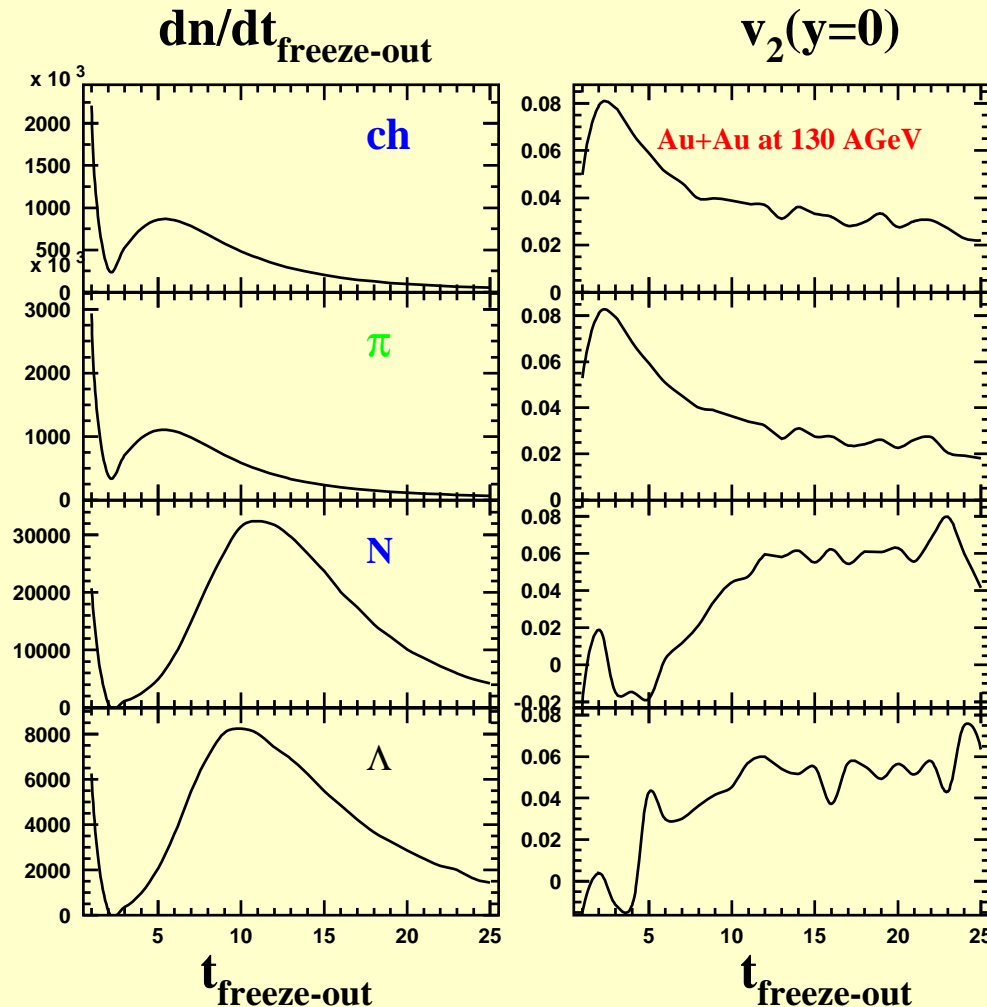
(1) Substantial part of hadrons leaves the system immediately after their production within the first two fm/c.

(2) Baryons and mesons are completely different: pions emitted within the first few fm/c carry the strongest flow. In contrast to pions, the baryon fraction acquires stronger elliptic flow during the subsequent rescatterings, developing the hydro-like flow.

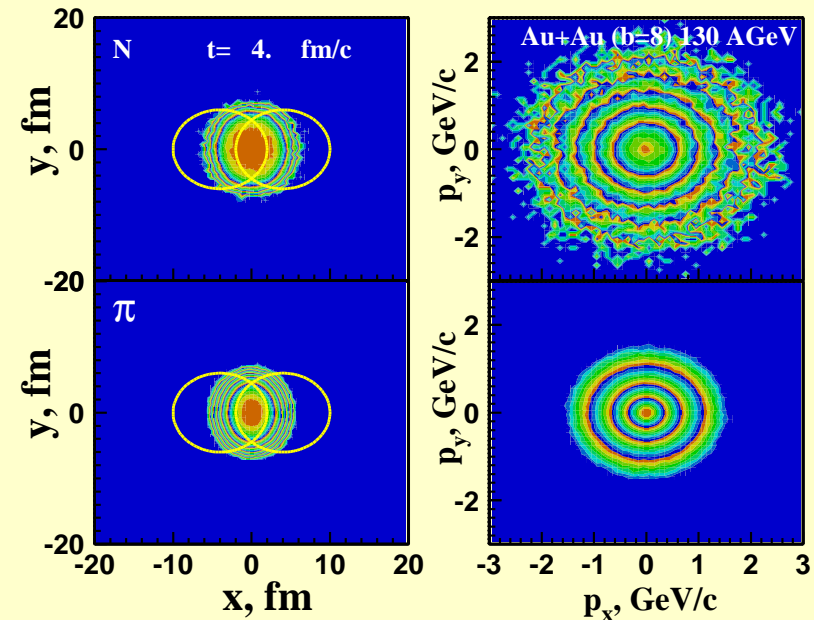# Freeze-out and Elliptic Flow of π, N at RHIC

Anisotropy in coordinate space and elliptic flow of nucleons and pions in **Au+Au** collisions at $\sqrt{s} = 130$ **AGeV** with the impact parameter $b = 8$ **fm.**

t = 2 fm/c

t = 4 fm/c

Strong anisotropy in coordinate space, but weak anisotropy in the momentum space

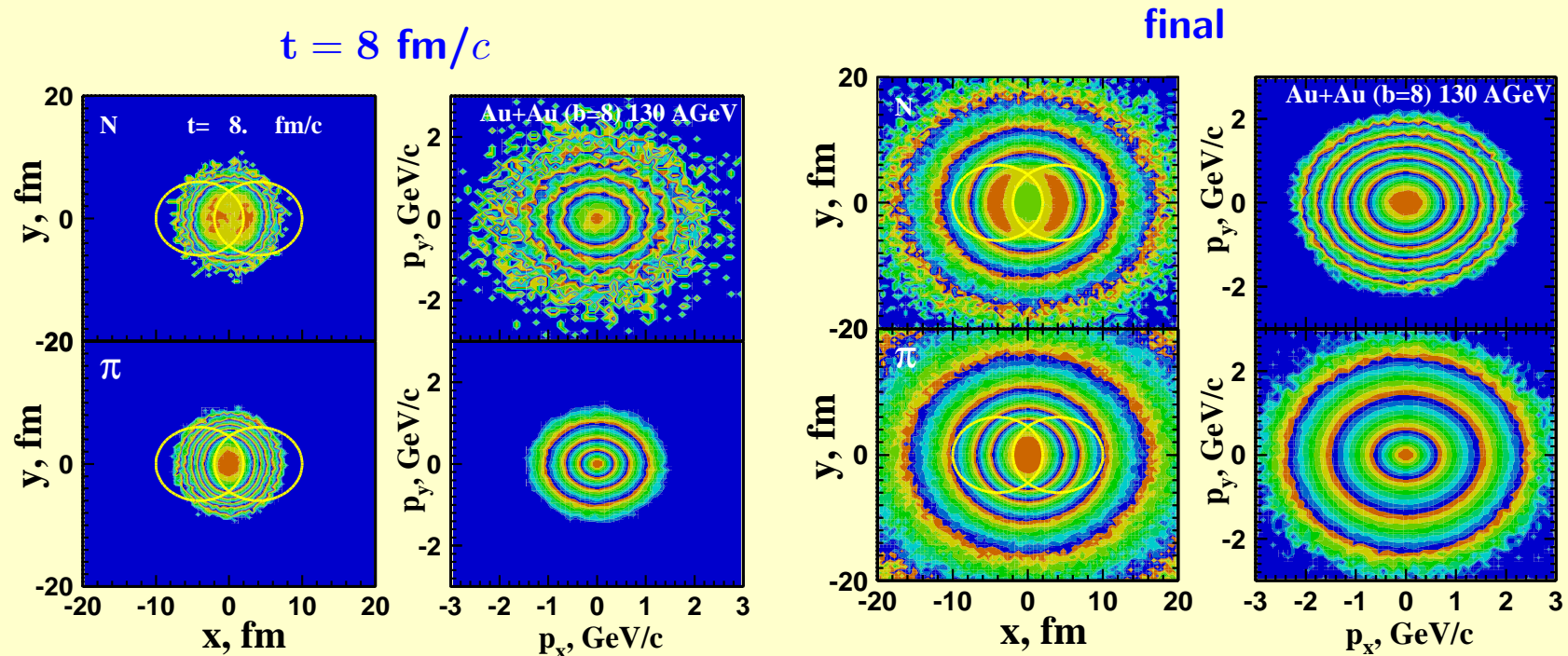**Anisotropy starts to develop in the momentum space for low momenta**

Freeze-out and Elliptic Flow of π, N at RHIC

Anisotropy in coordinate space and elliptic flow of nucleons and pions in **Au+Au** collisions at $\sqrt{s} = 130$ **AGeV** with the impact parameter $b = 8$ **fm.**

t = 8 fm/c

final

Nucleons leave the overlapping region; at the end of the reaction we see the pronounced maxima at centers of nuclei. Most of the **pions** is staying within the overlapping area till the end of reaction

The anisotropy in coordinate space (almond-shaped region) is transformed into the anisotropy in the momentum space.

Freeze-out and Elliptic Flow of K, Λ at RHIC

Anisotropy in coordinate space and elliptic flow of kaons and lambdas in Au+Au collisions at $\sqrt{s} = 130$ AGeV with the impact parameter $b = 8$ fm.

$t = 2$ fm/c

$t = 4$ fm/c

Strong anisotropy in coordinate space, but weak anisotropy in the momentum space

Anisotropy starts to develop in the momentum space for low momenta

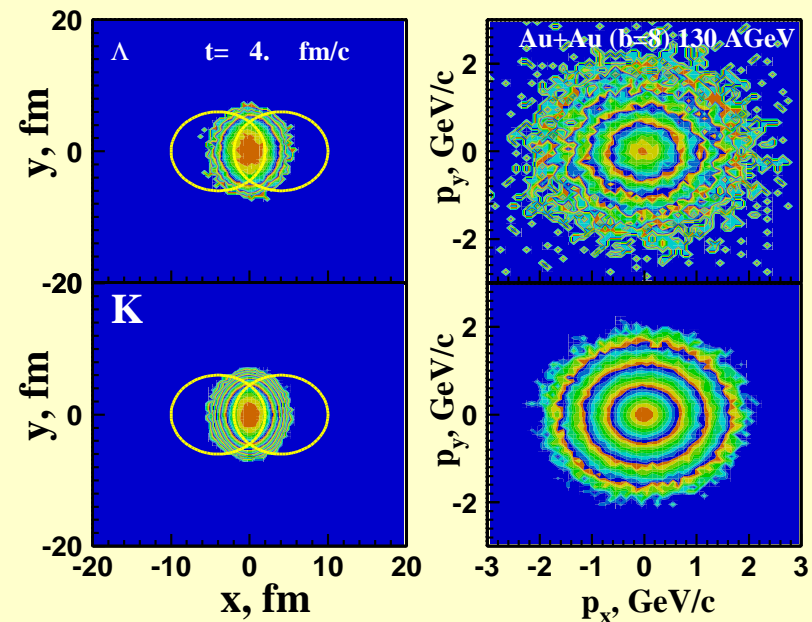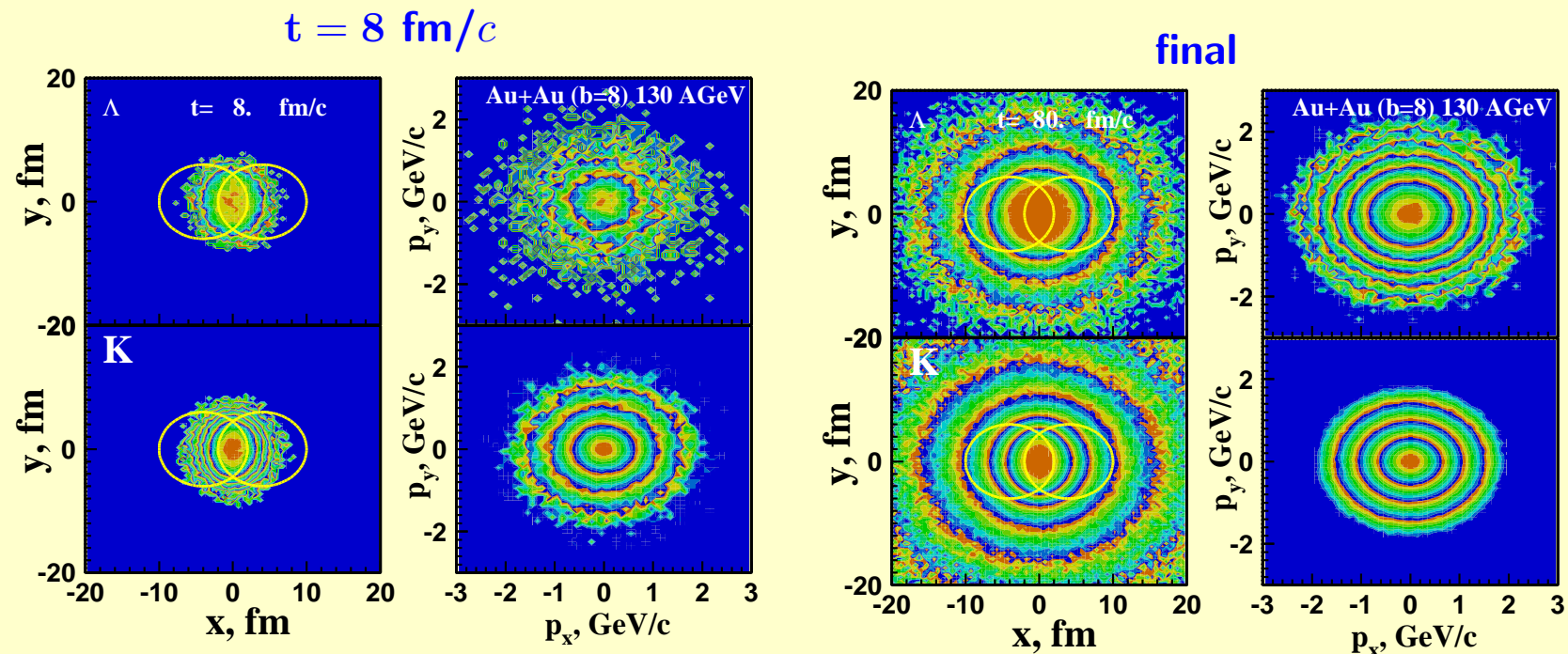# Freeze-out and Elliptic Flow of K, Λ at RHIC

Anisotropy in coordinate space and elliptic flow of kaons and lambdas in **Au+Au** collisions at $\sqrt{s} = 130$ **AGeV** with the impact parameter $b = 8$ **fm.**

$t = 8$ **fm/c**

final
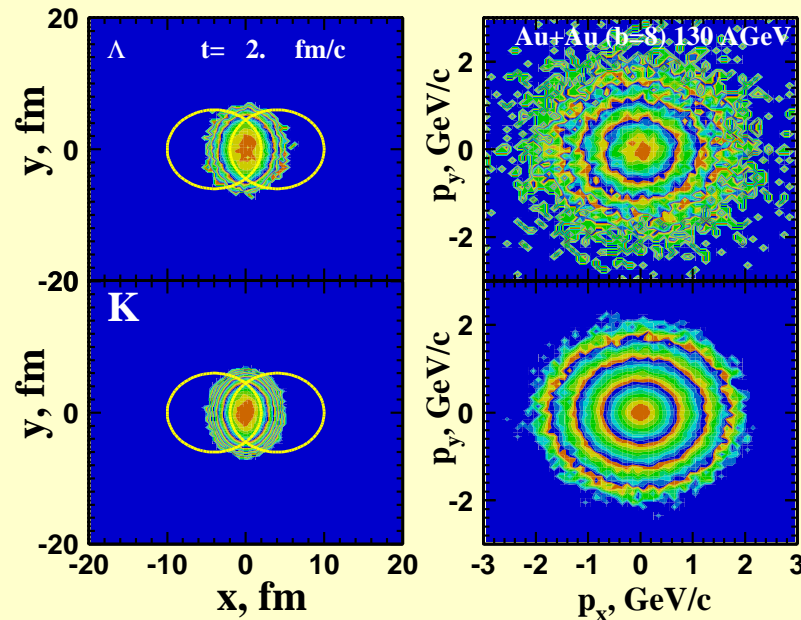
$\mathbf{d^2N/dxdy}$ for Λ at 80 fm/c has wide plateau between centers of colliding nuclei. $\mathbf{d^2N/dxdy}$ for kaons is much narrower; like pions, kaons are mostly concentrated in the overlapping region

The momentum-space anisotropy for baryons is much stronger than that for mesons

Freeze-Out and Flow

v₂(y=0)   **s₂(y=0)**   **v₂/s₂(y=0)**
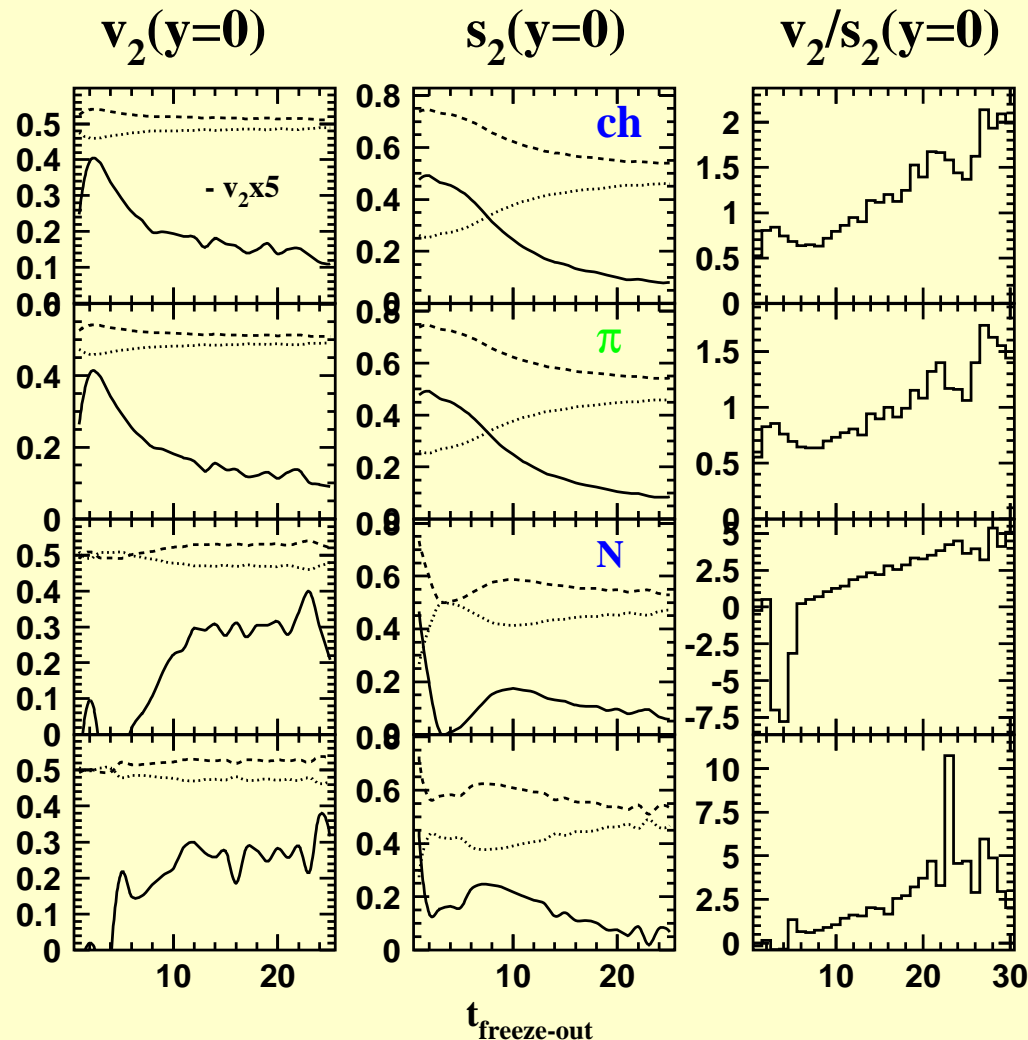
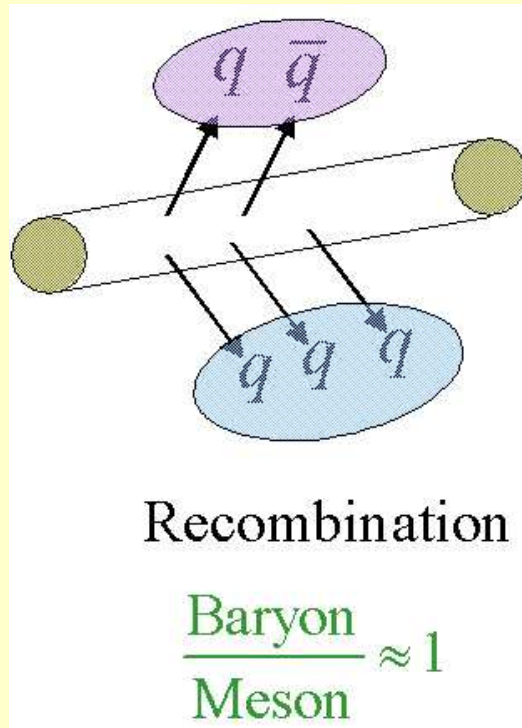$t_{freeze-out}$

(1) $v_2 = v_2^x - v_2^y$:
For **pions** v_2^x (v_2^y) **falls down (grows)** with $t_{freeze-out}$ while for **nucleons** it is opposite.

(2) $s_2 = s_2^x - s_2^y$:
the **difference between** s_2^x and s_2^y is more pronounced than the difference between v_2^x and v_2^y, but the behaviour is very similar.

Recombination Models

Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$
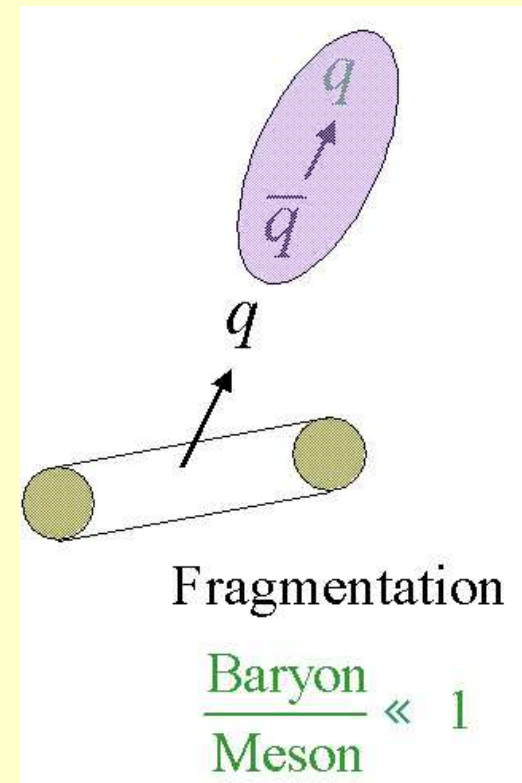
Recombination: no further branching of partons occurs (i.e. some sort of thermal equilibrium is reached in the parton phase)

Fragmentation: partonic content of hadrons comes from gluons and $q\bar{q}$ pairs emitted from the fragmenting parton

Conclusions

❖ **In microscopic model the system of final particles in heavy-ion collision can be represented as a core and a halo. The core contains the particles which are still in evolution through the inelastic and elastic collisions. The halo is represented by particles which are already decoupled from the system and move to the detectors.**

❖ **The shapes of the emitting sources are far from Gaussians. In addition, the τ- scaling, which is often used in the parameterizations, is not confirmed by the model calculations for heavy systems like Au+Au.**

❖ **Different species decouple at different times. The order of the freeze-out of hadronic species is as follows: 1 - pions; 2 - kaons; 3 - lambdas; 4 - nucleons.**

❖ **At RHIC: Significant fractions of mesons and baryons are emitted within the first two fm/c.**

❖ **Mesons with large P_T are predominantely produced at the early stages of the reaction, whereas the low-P_T component is populated by mesons coming from the decays of resonances.**

❖ **Elliptic flow depends strongly on particle freeze-out. Mesons: the freeze-out picture is opposite to the evolution one. The earlier the freeze-out of mesons, the stronger the $v_2^M(y=0)$, while the v_2 of baryons frozen earlier is weaker than the v_2 of baryons frozen later on.**